

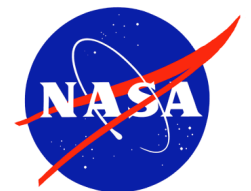
A SELECTION OF COMPOSITES SIMULATION PRACTICES AT NASA LANGLEY RESEARCH CENTER

**James G. Ratcliffe
Senior Research Scientist
National Institute of Aerospace, Hampton VA**

**Resident at Durability, Damage Tolerance and Reliability Branch,
NASA Langley Research Center**

**MSC Software
Composites Consortium Meeting**

**May 3 – May 4, 2007
Santa Ana, CA**





OUTLINE

- **National Institute of Aerospace (NIA) overview**
- **NASA Langley (LaRC) overview**
- **Examples of composites simulation:**
 - Thermo-mechanical material model
 - Damage analyses of composites
 - Progressive damage material model
 - Virtual crack closure technique (VCCT)
 - Decohesion element
 - Flight 587 structures investigation
 - Rotorhub flexbeam analysis
 - Mixed-mode delamination failure criterion
 - Delamination in z-pin reinforced laminates
- **Concluding remarks**



NATIONAL INSTITUTE OF AEROSPACE

- An Independent Non-profit Research and Graduate Education Institute formed in 2002 by a Consortium of Six Universities and the AIAA Foundation
- Conceived by NASA Langley Research Center and established to serve as LaRC's Collaborative Partner
- Conducts Collaborative **Research** in Engineering and Science relevant to Aerospace
 - Georgia Tech
 - Virginia Tech
 - University of Virginia
 - University of Maryland
 - North Carolina A&T State University
 - Old Dominion University
 - College of William & Mary
 - Hampton University



COMPOSITE RESEARCH ACTIVITIES AT NASA LANGLEY



- Computational materials
- Crash worthiness of composite structures
- Structural tailoring with composites
- Manufacturing and fabrication technology
- Health monitoring using embedded sensors
- Residual strength and damage propagation
- Influence of generalized imperfections on composite shell response
- Delamination and crack growth
- Thermo-mechanical material response
- Multidisciplinary design environments
- Uncertainty quantification for composite designs
- Impact response and strain rate sensitivity



SIMULATION ISSUES FOR COMPOSITES

- Variabilities in composite design (fiber placement, fiber angle, thickness, volume fraction, failure modes, etc)
- Visualization of composite simulation results
- Micro-mechanics through macro-mechanics - Problem of scale (global local analysis requirements)
- Computational models for new and evolving materials
- Computational models for incorporating mechanical-based failure models
- Failure initiation and damage propagation of different composite architectures (sandwich construction, integrally-stiffened sections, etc)
- Corroborating experimental program for validation of analysis

At NASA Langley, these issues are addressed by researchers using:

1. User-defined material models
2. User-defined element routines
3. User-developed pre and post-processing software



NASA LANGLEY RESEARCH CENTER

Research Technology Directorate (RTD) consists of 21 branches:

Configuration Aerodynamics Branch	Advanced materials and Processing Branch	Aeroacoustics Branch	Safety-Critical Avionics Systems Branch
Computational Aerosciences Branch	Aeroelasticity Branch	Applied Technologies and Testing Branch	Structural Acoustics Branch
Flow Physics and Controls Branch	Durability, Damage Tolerance and Reliability Branch	Dynamic Systems and Controls Branch	Structural Dynamics Branch
Advanced Sensing and Optical Measurement Branch	Gas, Fluid and Acoustics Research Support Branch	Flight Dynamics Branch	
Aerothermodynamics Branch	Structural Mechanics and Concepts Branch	Crew Systems and Aviation Operations Branch	
Hypersonic Airbreathing Propulsion Branch	Nondestructive Evaluation Sciences Branch	Electromagnetics and Sensors Branch	



THERMO-MECHANICAL MATERIAL MODEL

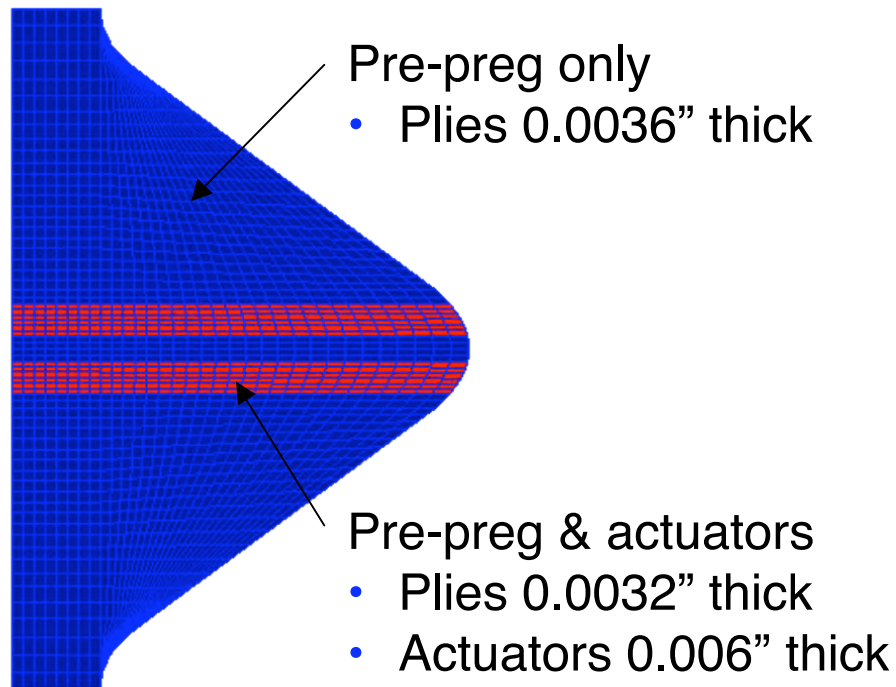
TRAVIS TURNER

**STRUCTURAL ACOUSTICS BRANCH
NASA LANGLEY RESEARCH CENTER
HAMPTON, VA**

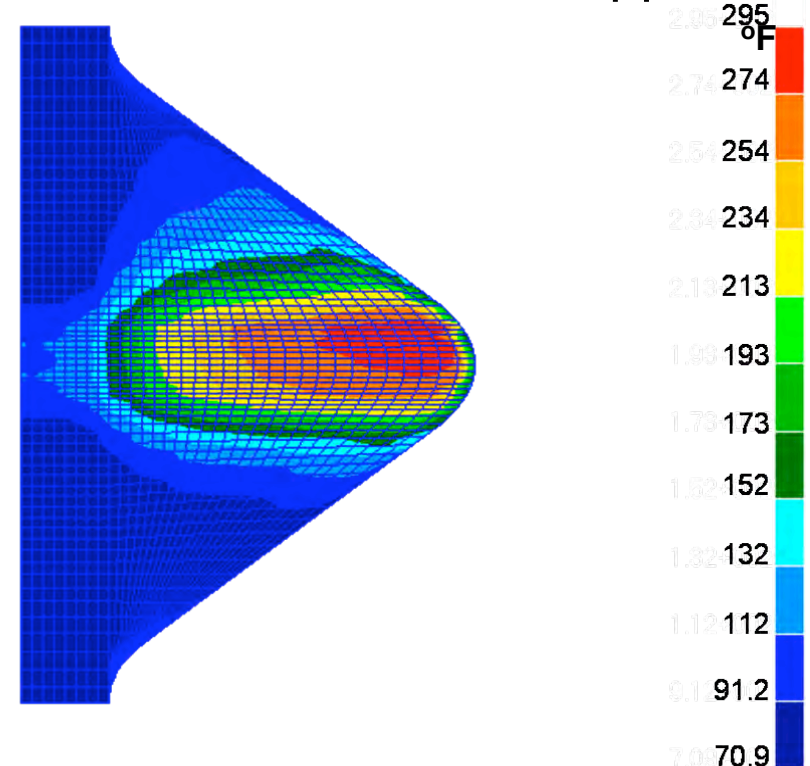


NUMERICAL MODEL

Shell Element Mesh



Meas. Thermal Load Applied

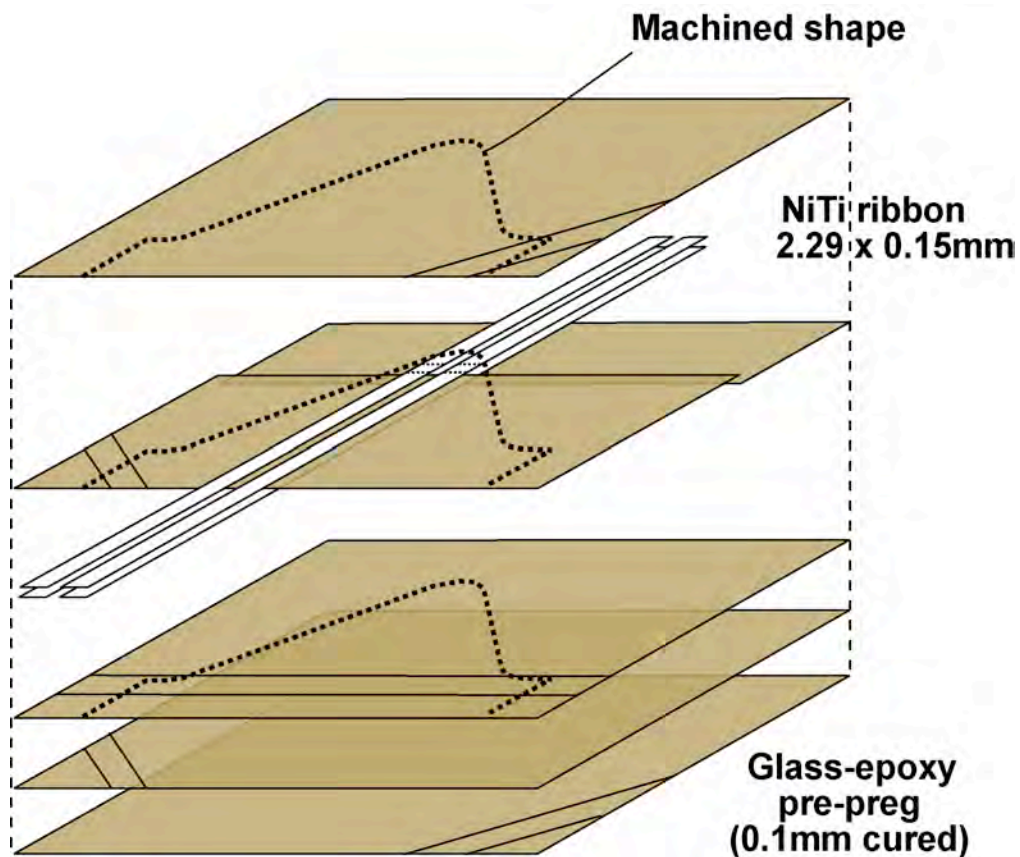


- Developed thermo-mechanical FE model based upon LaRC-developed constitutive model implemented in MSC.Nastran and ABAQUS
- Shell element mesh separates glass-epoxy-only and SMAHC element types
- Nonlinear static solution performed with imposed temperature load specified by experimental measurements at critical temperatures

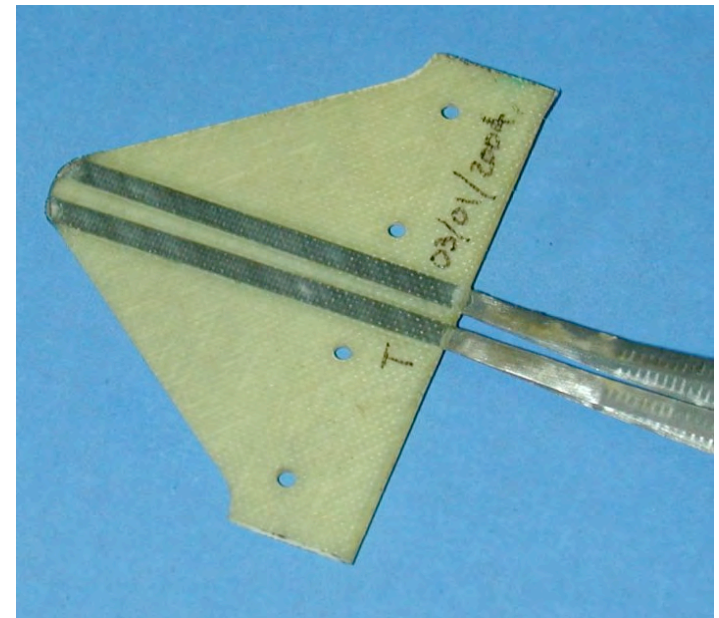


STRUCTURAL DEFLECTION CONTROL

Actuators embedded within layers of a laminated composite structure



Completed Flow Effector

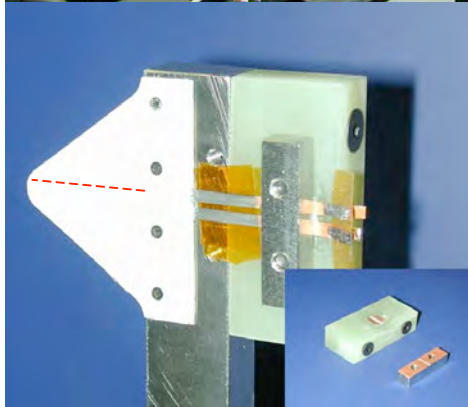
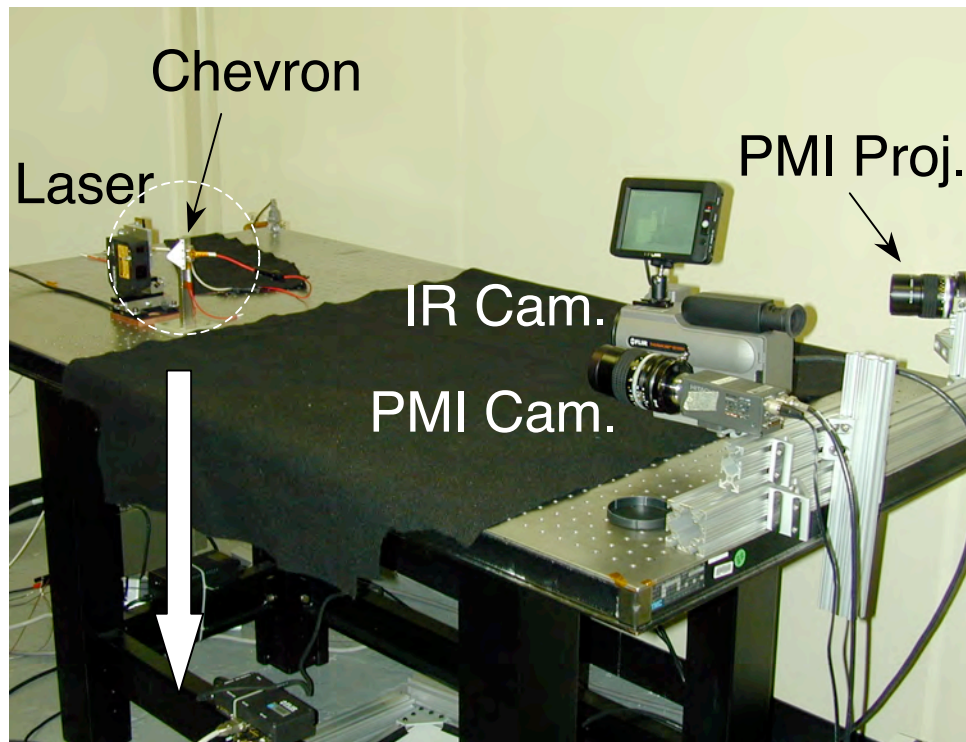


- Discrete actuator “inclusion”
- Non-uniform consolidated pre-preg ply thickness
- Non-uniform temperature distribution in service

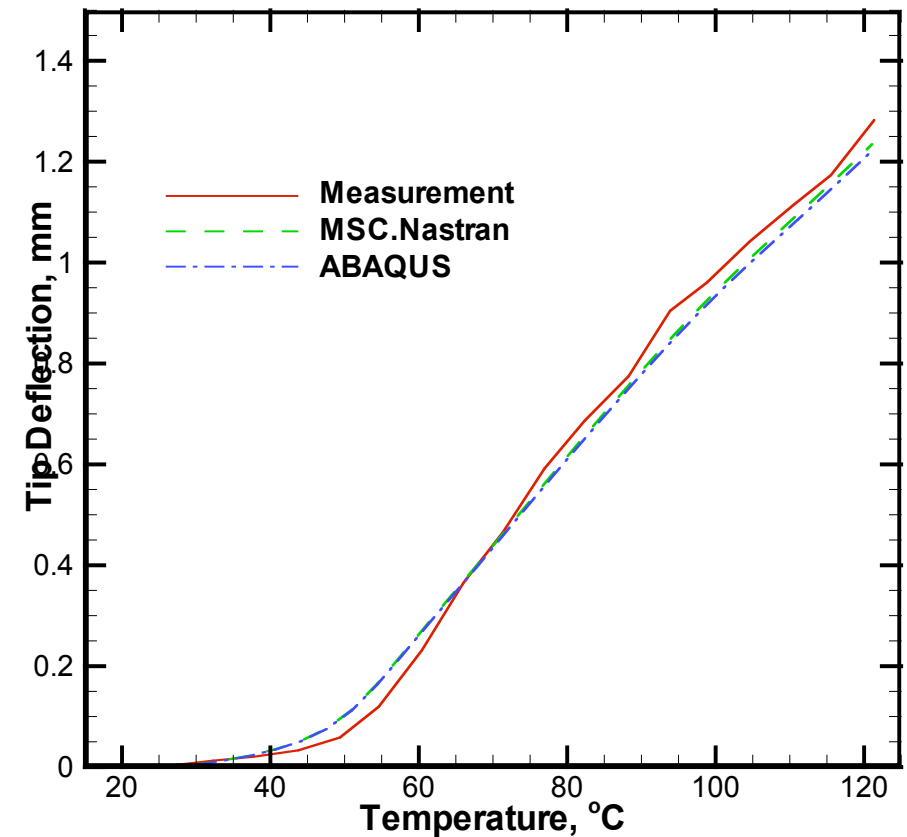
Flow Effector Deflection Control



Bench Top Test System



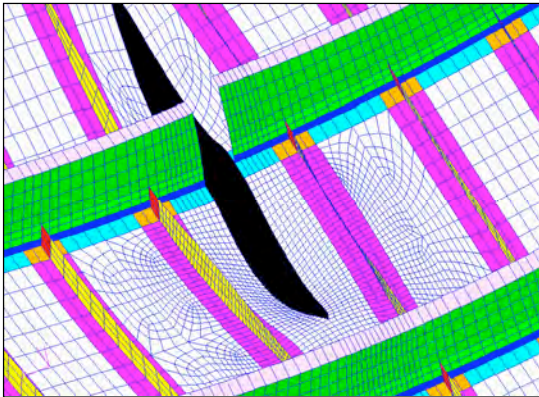
Tip Deflection Comparison



- Excellent numerical-experimental agreement
- Numerical design tool validated

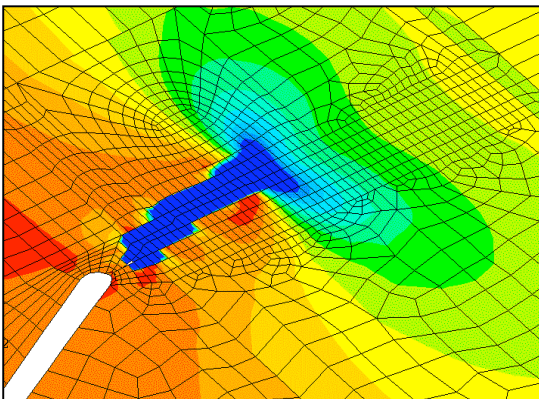


DAMAGE ANALYSES OF COMPOSITES



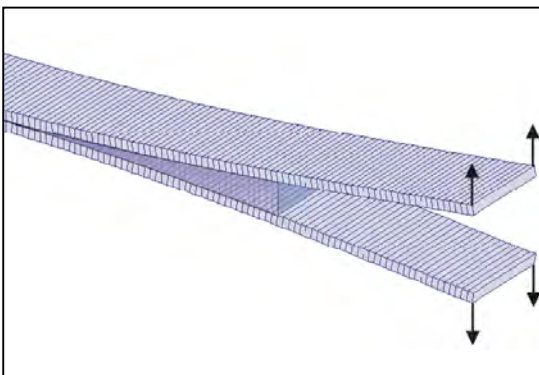
Through-the-thickness crack

- fracture mechanics and modifications
- strain softening



Ply Damage

- continuum damage modeling (CDM)
- strength-based methods (criteria)
- micromechanics approach



Delamination/Debonding

- fracture mechanics approaches (VCCT)
- decohesion elements



PROGRESSIVE FAILURE MATERIAL MODEL

NORMAN F. KNIGHT

**GENERAL DYNAMICS
ADVANCED INFORMATION SYSTEMS
CHANTILLY, VA**

**Resident at Durability, Damage Tolerance and
Reliability Branch, NASA Langley Research Center**



PFA/PDA SIMULATIONS

- Develop user-defined material subroutine UMAT for PFA and user-defined element subroutine UEL for PDA using ABAQUS/Standard
- UMAT features linear elastic, bimodulus, orthotropic material model for a composite laminate
- Failure initiation based on material allowable values using:
 - Maximum stress criteria
 - Maximum strain criteria
 - Hashin criteria
 - Tsai-Wu polynomial failure criterion
- Material degradation based on degrading elastic material stiffness coefficients for a particular failure direction resulting in near zero stress for that component - rather than degrading engineering properties
- Material degradation can be instantaneous or recursive over several solution steps
- Delamination and crack growth modeling using Boeing fracture interface element (VCCT approach) using user-defined element subroutine UEL



TYPICAL FAILURE INITIATION CRITERIA

- **Maximum stress criteria**

$$\begin{aligned}\frac{\sigma_{11}}{X_T} &\leq 1 \text{ for } \sigma_{11} \geq 0; & \frac{|\sigma_{11}|}{X_C} &\leq 1 \text{ for } \sigma_{11} \leq 0 \\ \frac{\sigma_{22}}{Y_T} &\leq 1 \text{ for } \sigma_{22} \geq 0; & \frac{|\sigma_{22}|}{Y_C} &\leq 1 \text{ for } \sigma_{22} \leq 0 \\ \frac{\sigma_{33}}{Z_T} &\leq 1 \text{ for } \sigma_{33} \geq 0; & \frac{|\sigma_{33}|}{Z_C} &\leq 1 \text{ for } \sigma_{33} \leq 0 \\ \frac{|\tau_{12}|}{S_{XY}} &\leq 1; & \frac{|\tau_{23}|}{S_{YZ}} &\leq 1; & \frac{|\tau_{13}|}{S_{XZ}} &\leq 1\end{aligned}$$

- **Tsai-Wu polynomial failure criterion**

$$\begin{aligned}\phi = & F_1\sigma_{11} + F_2\sigma_{22} + F_3\sigma_{33} + F_{11}(\sigma_{11})^2 + F_{22}(\sigma_{22})^2 + F_{33}(\sigma_{33})^2 \\ & + 2F_{12}\sigma_{11}\sigma_{22} + 2F_{23}\sigma_{22}\sigma_{33} + 2F_{13}\sigma_{11}\sigma_{33} \\ & + F_{44}(\sigma_{13})^2 + F_{55}(\sigma_{23})^2 + F_{66}(\sigma_{12})^2 \geq 1\end{aligned}$$



TYPICAL MATERIAL DEGRADATION

- 3D stress-strain relations

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \sigma_{33} \\ \sigma_{12} \\ \sigma_{13} \\ \sigma_{23} \end{Bmatrix} = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{12} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{13} & C_{23} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \begin{Bmatrix} \epsilon_{11} \\ \epsilon_{22} \\ \epsilon_{33} \\ \gamma_{12} \\ \gamma_{13} \\ \gamma_{23} \end{Bmatrix}$$

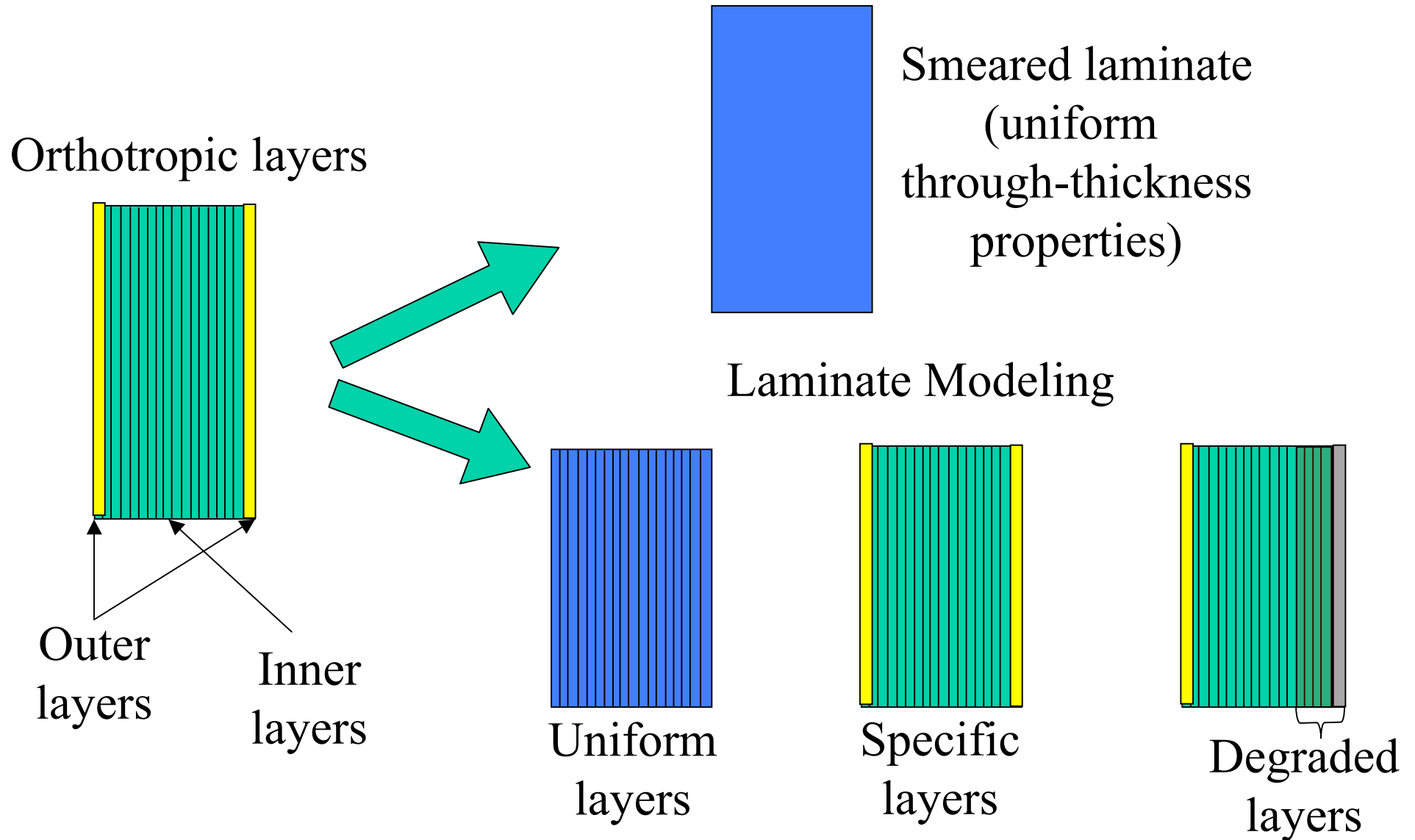
- Material degradation of the i^{th} row and column of the constitutive matrix [C] when the i^{th} stress component indicates failure
- Off-diagonal terms set to zero; diagonal term degraded by factor b_i

$$C_{ij}^{\text{degraded}} = C_{ji}^{\text{degraded}} = 0 \text{ for } i \neq j$$

$$C_{ii}^{\text{degraded}} = \beta_i C_{ii}$$



MATERIAL MODELING OPTIONS





THE VIRTUAL CRACK CLOSURE TECHNIQUE

RONALD KRUEGER

**NATIONAL INSTITUTE OF AEROSPACE
HAMPTON, VA**

**Resident at Durability, Damage Tolerance and
Reliability Branch, NASA Langley Research Center**



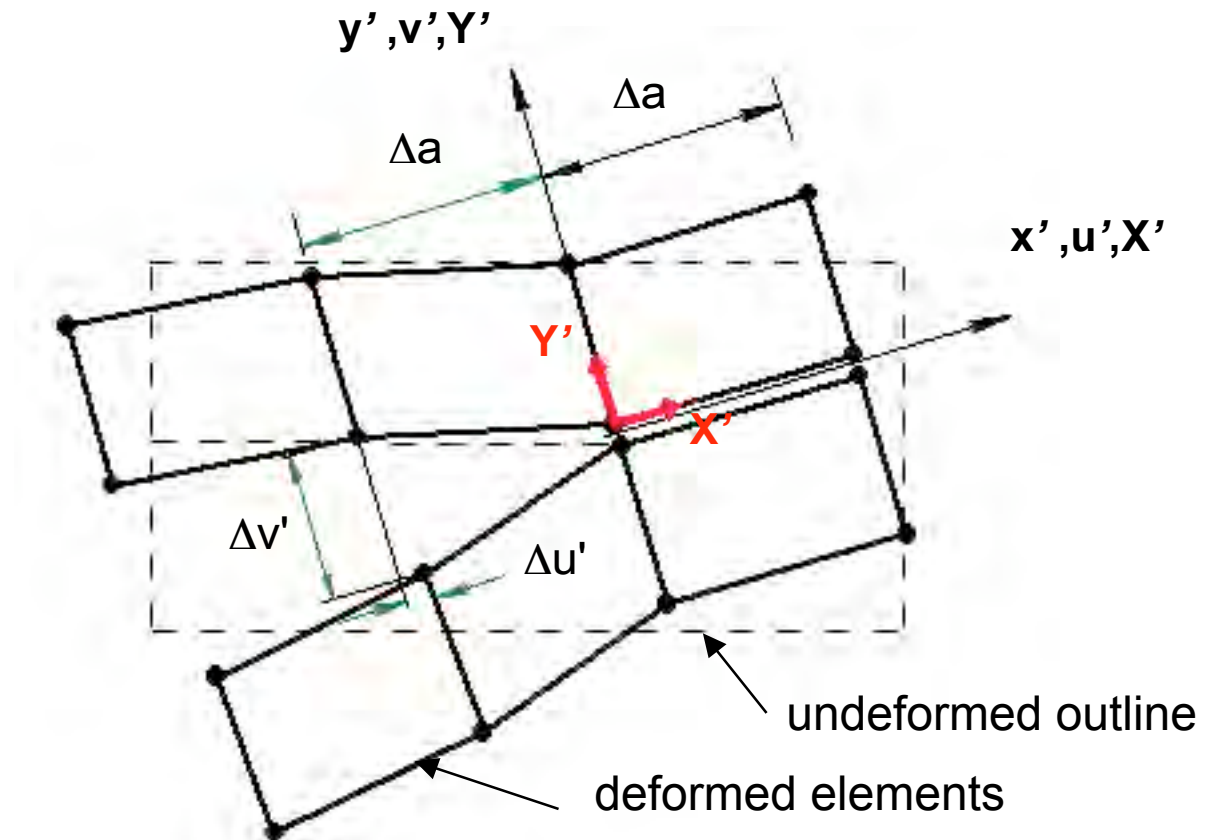
VIRTUAL CRACK CLOSURE TECHNIQUE (VCCT)*

- Two and three-dimensional analysis
- Nonlinear analysis
- Arbitrarily shaped delamination front
- 2D Finite Element Analysis

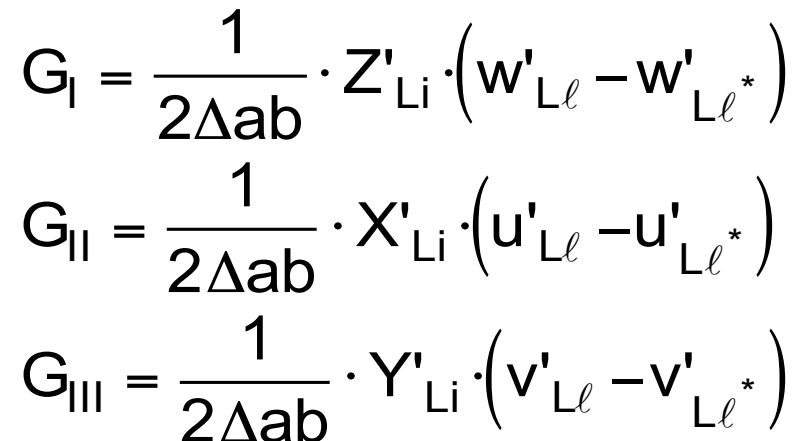
$$G_I = \frac{1}{2\Delta a} \cdot Y' \cdot \Delta v'$$

$$G_{II} = \frac{1}{2\Delta a} \cdot X' \cdot \Delta u'$$

$$G_T = G_I + G_{II}$$



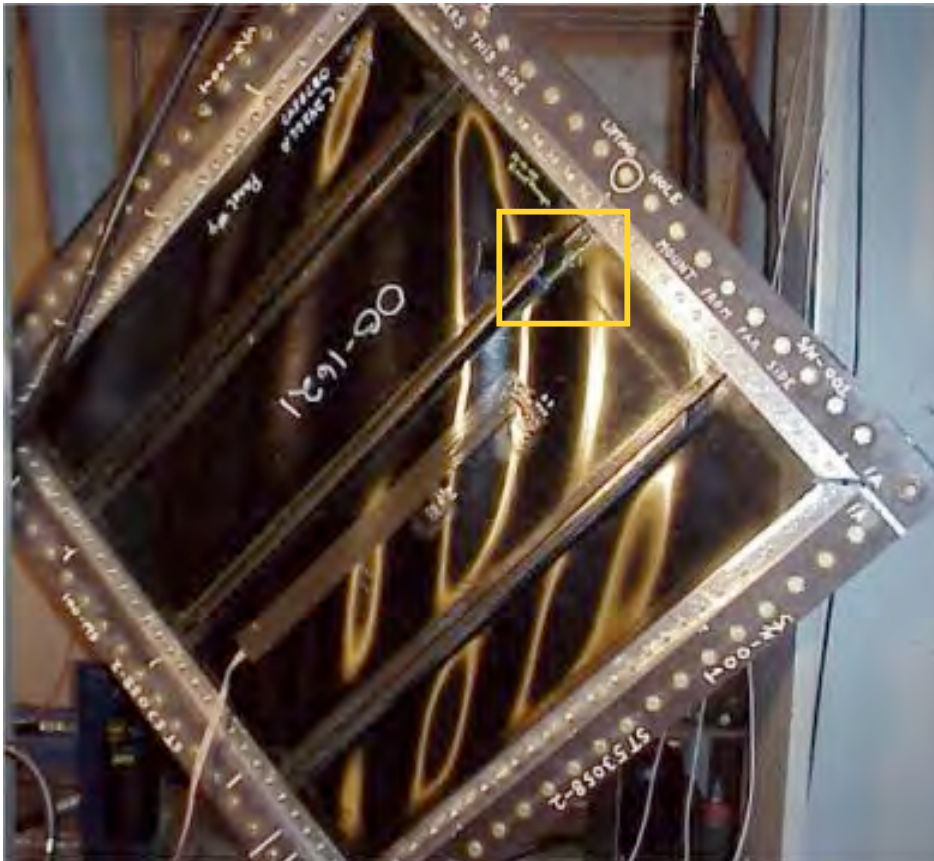
*Rybicki and Kanninen, Engineering Fracture Mechanics, 1977



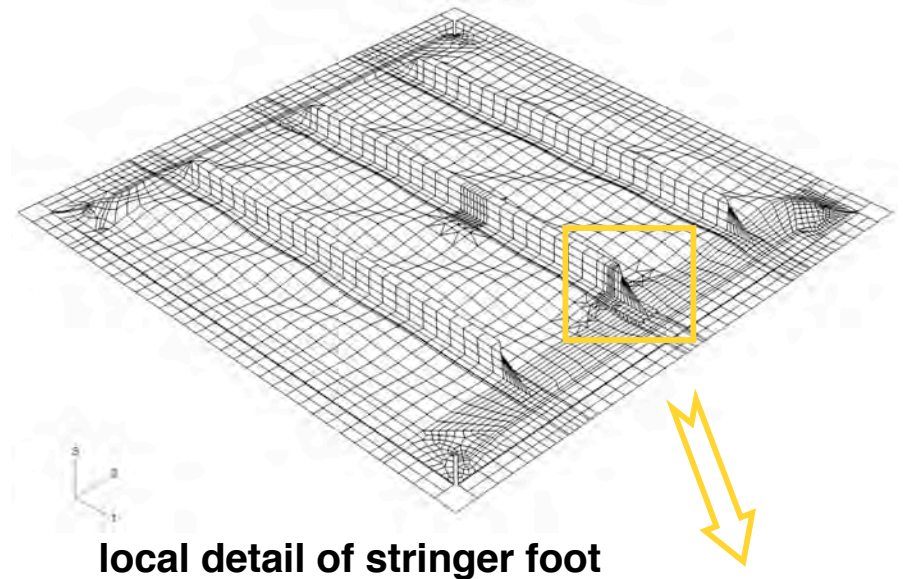
STRINGER STIFFENED PANEL SUBJECTED TO SHEAR LOADING



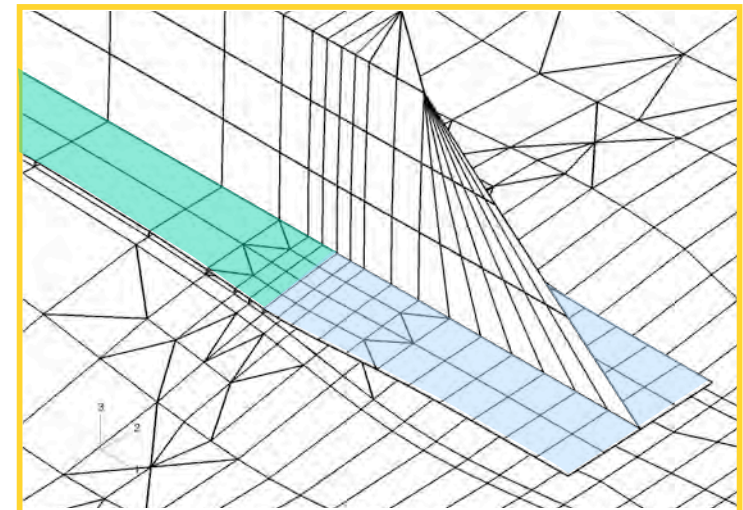
- Testing of Stiffened Shear Panel
Boeing, Philadelphia*



- Original Boeing ABAQUS Shell Model*

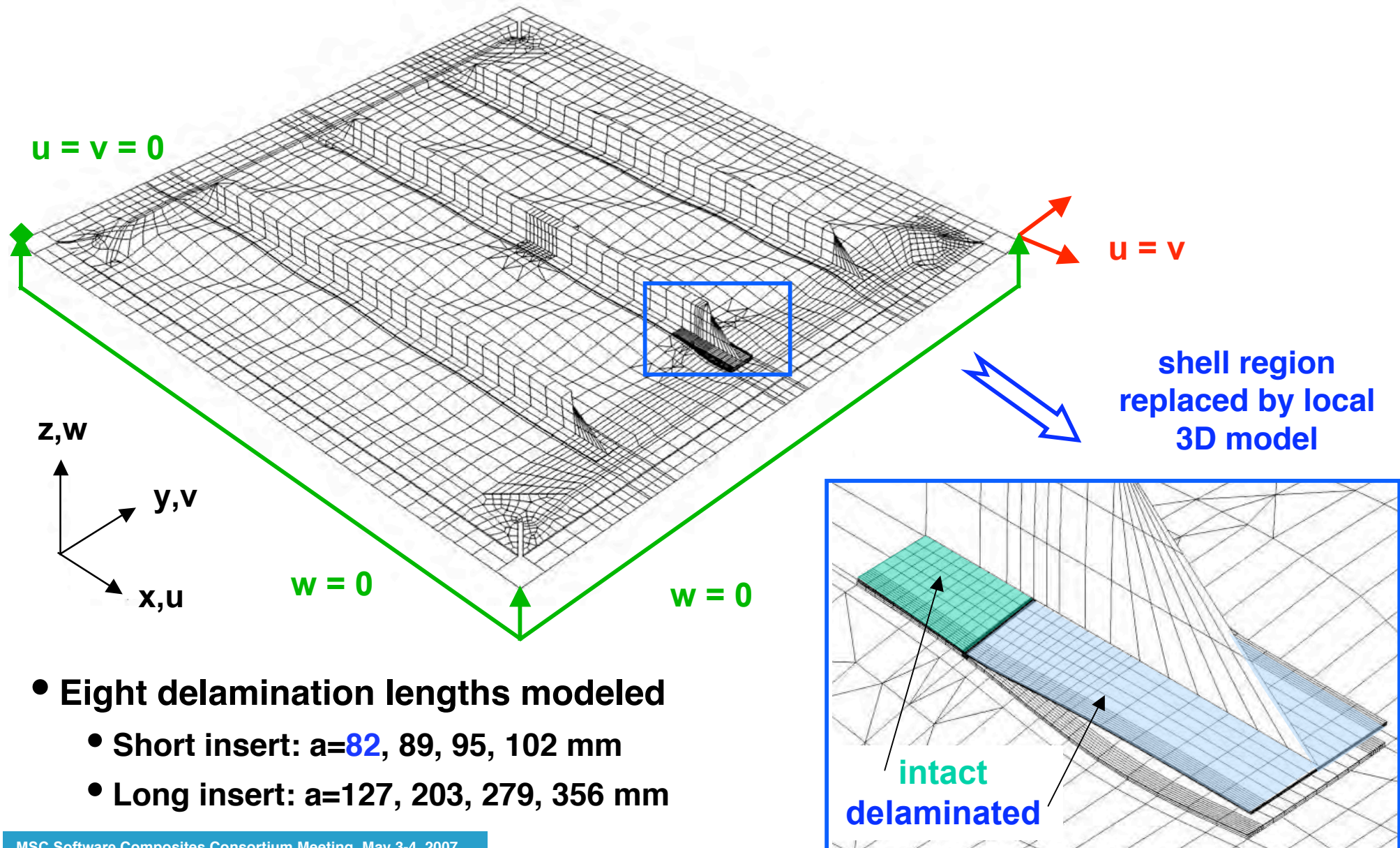


local detail of stringer foot



*Pierre Minguet, Boeing

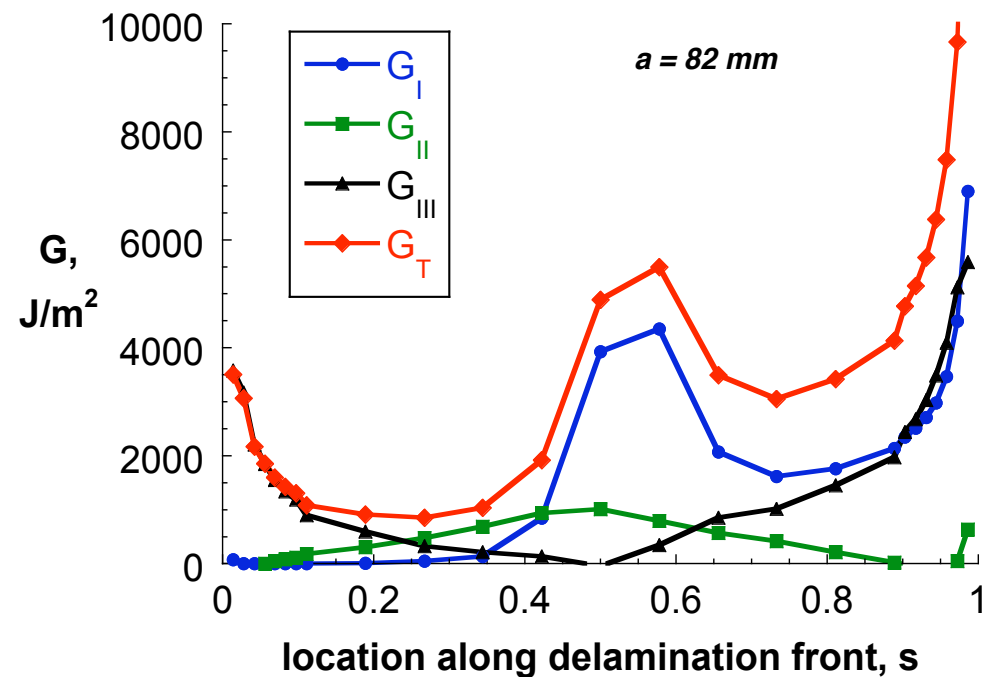
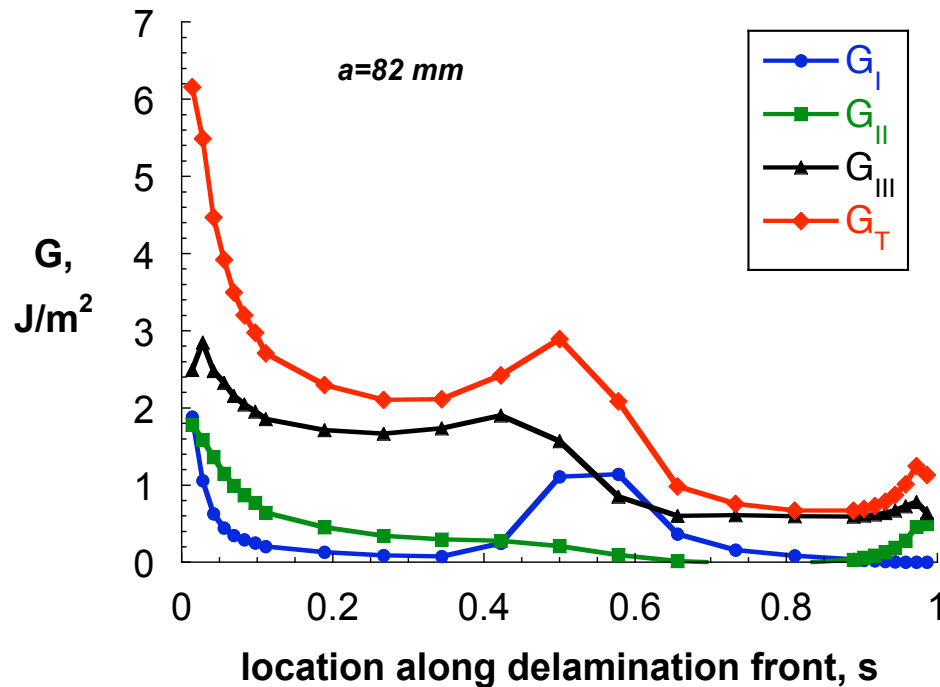
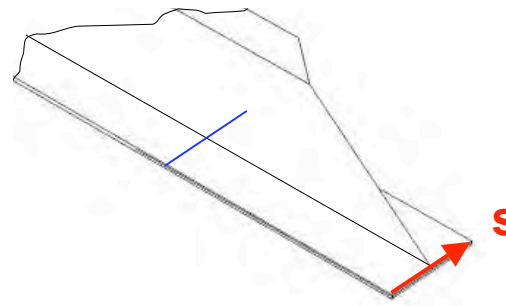
SHELL FE-MODEL WITH LOCAL 3D MODEL





COMPUTED ENERGY RELEASE RATES

- Increment 5, $u = v = 0.2$ mm, 3.3 %
- Increment 41, $u = v = 6.35$ mm, 100%





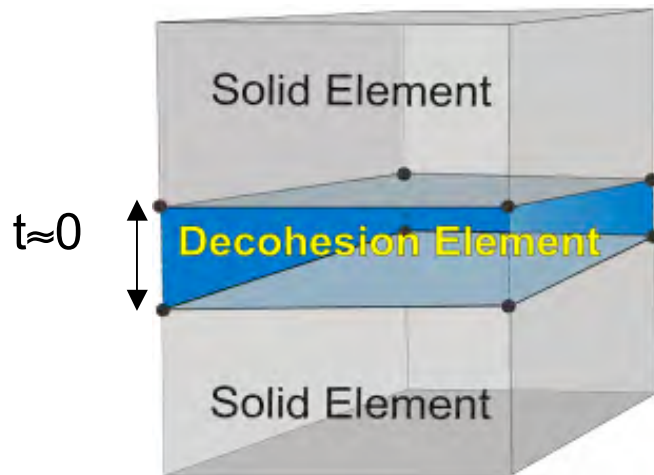
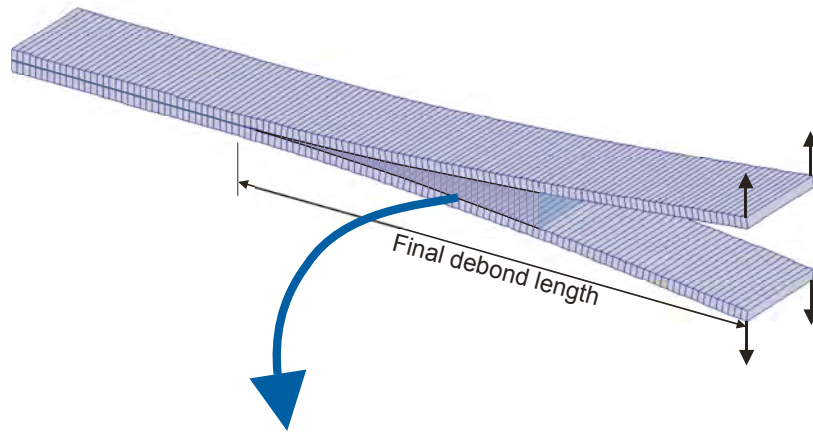
DECOHESION ELEMENTS FOR SIMULATING DELAMINATION

CARLOS DAVILA

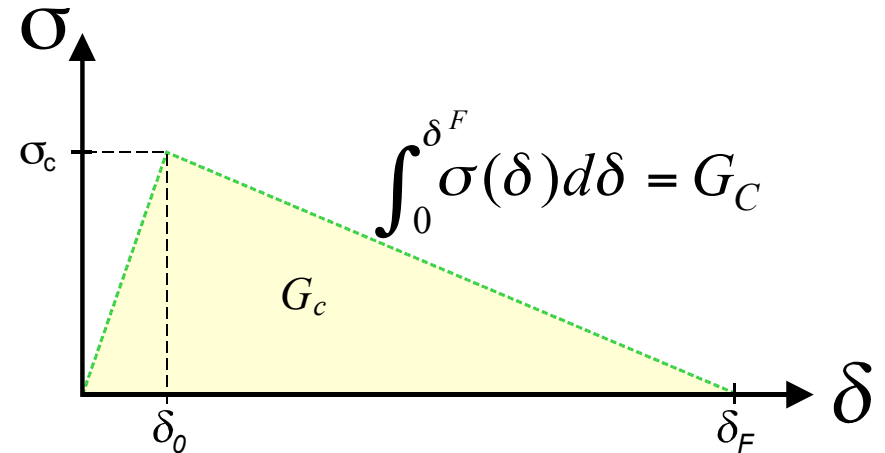
**DURABILITY, DAMAGE TOLERANCE AND
RELIABILITY BRANCH
NASA LANGLEY RESEARCH CENTER
HAMPTON, VA**



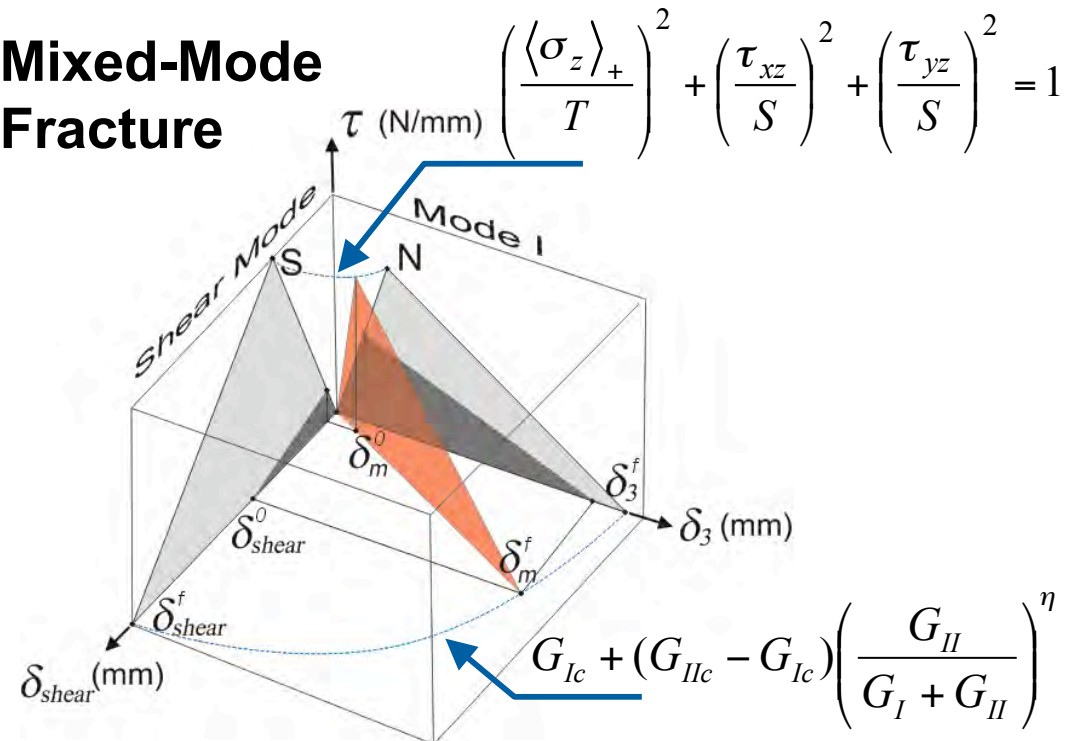
DECOHESION FINITE ELEMENT



Bilinear Traction-Displacement Law



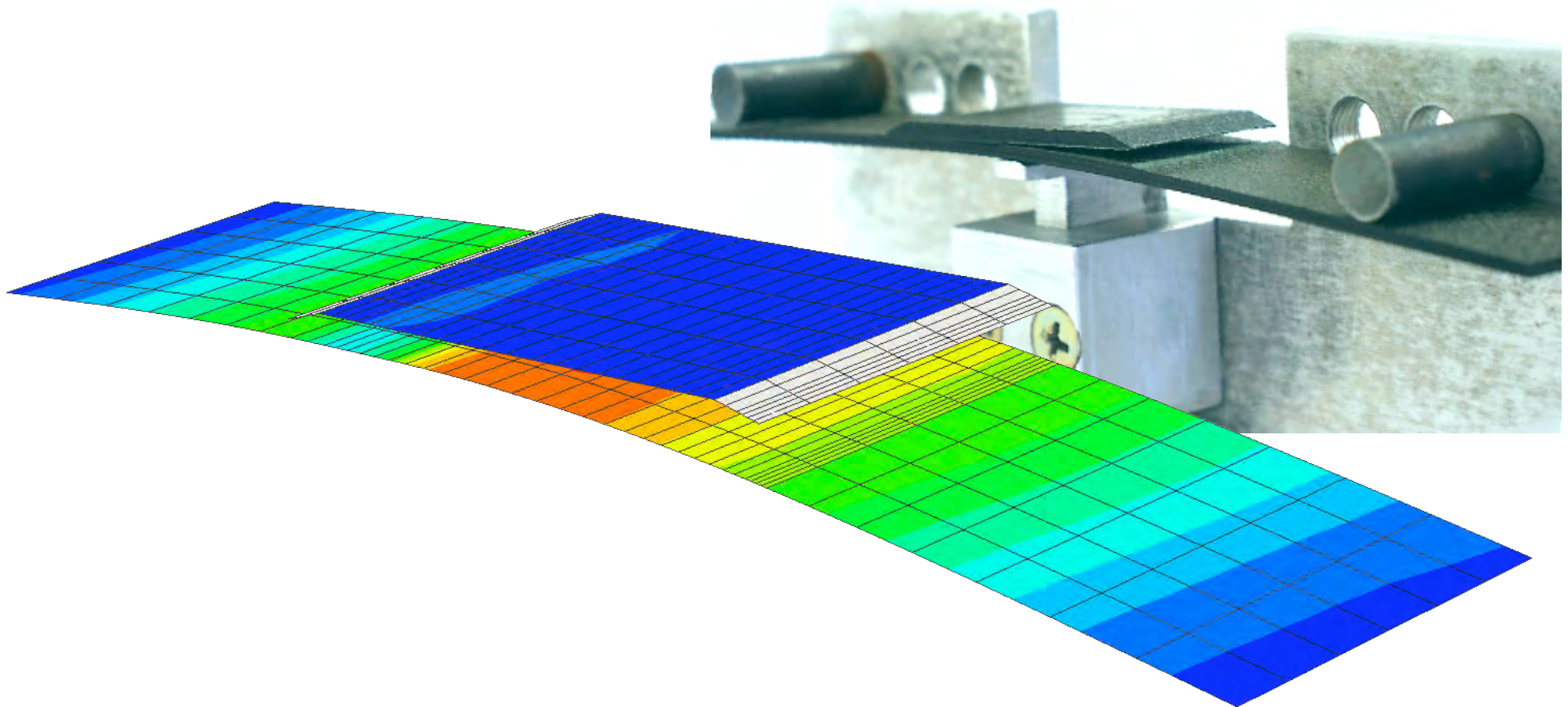
Mixed-Mode Fracture





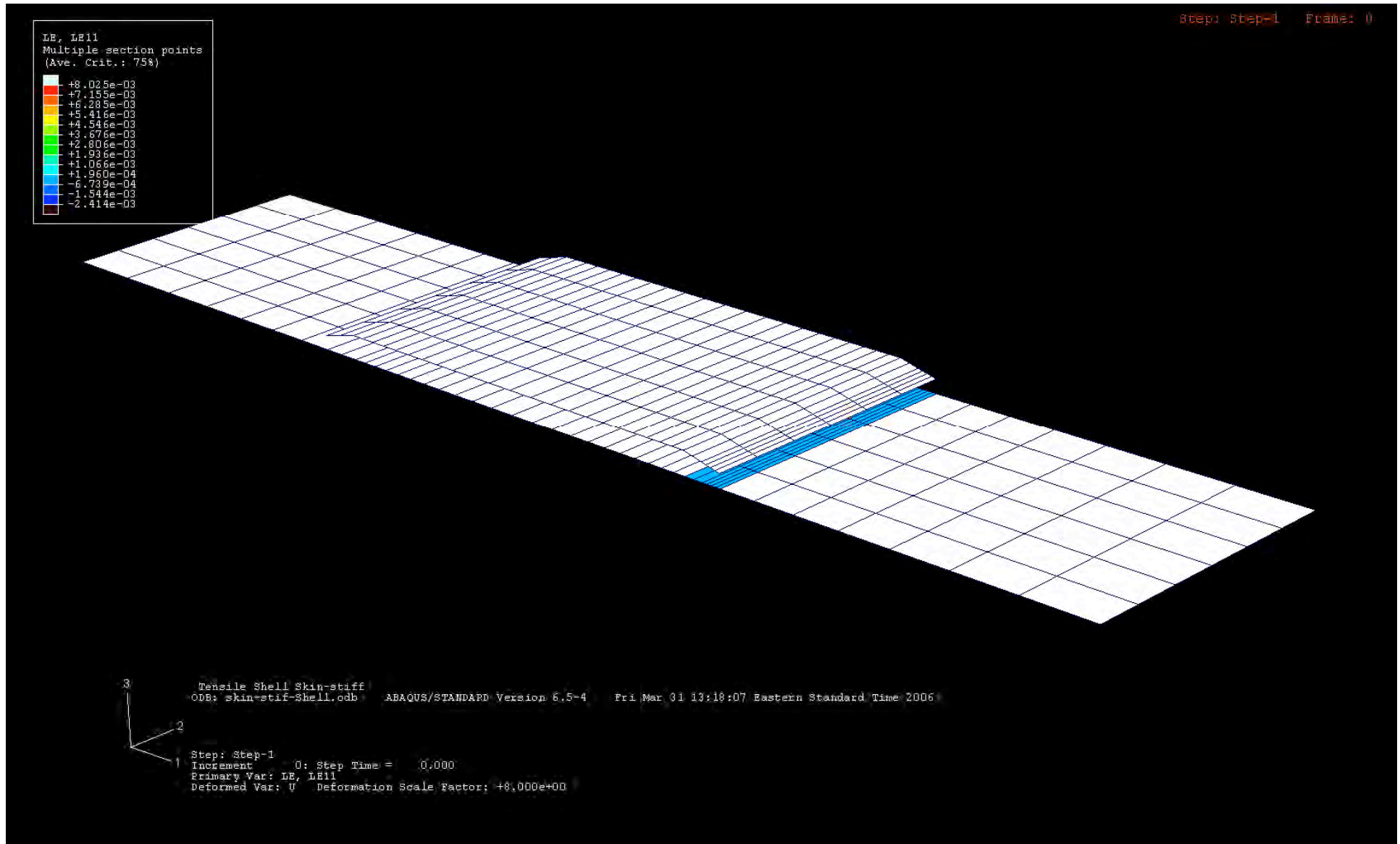
SKIN / STRINGER SEPERATION SPECIMEN

Decohesion elements used to predict delamination in skin / stringer specimen





SKIN / STRINGER SEPERATION SPECIMEN



NTSB Board Meeting AA Flight 587



Structures Investigation

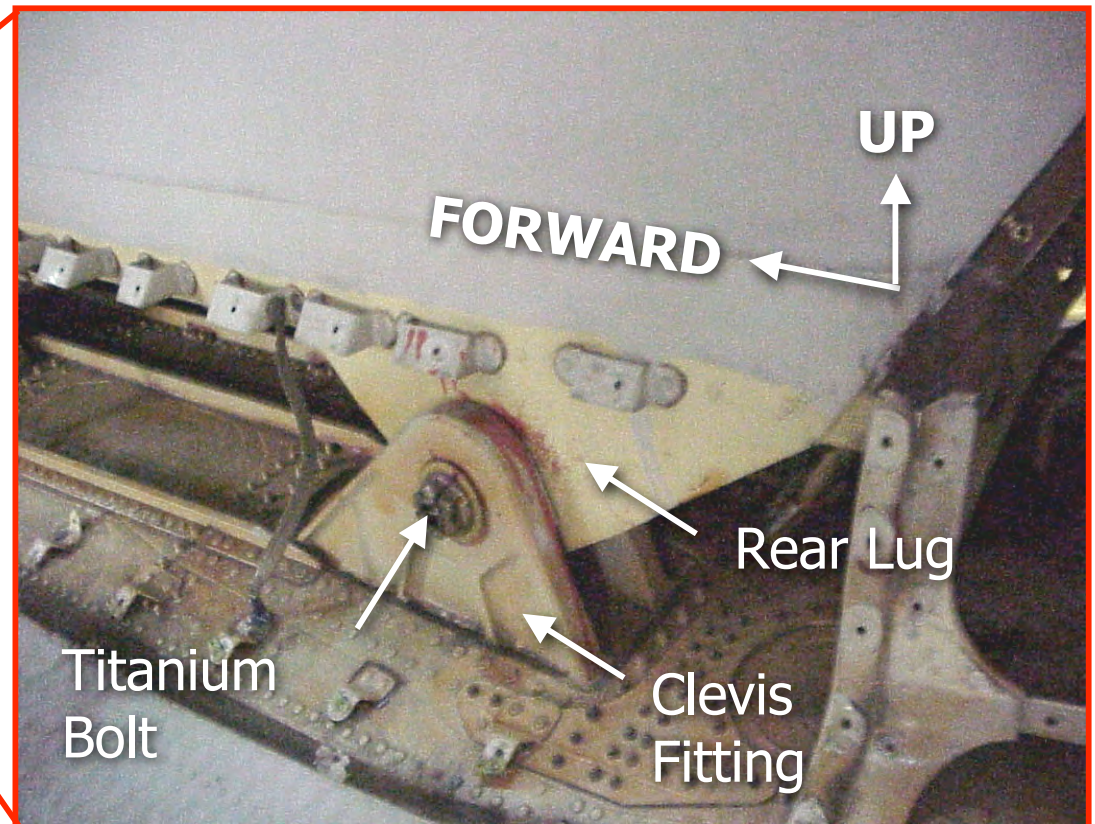
Brian K. Murphy - NTSB

Detailed Lug Analysis Team -
NASA LaRC





MAIN ATTACHMENT FITTINGS





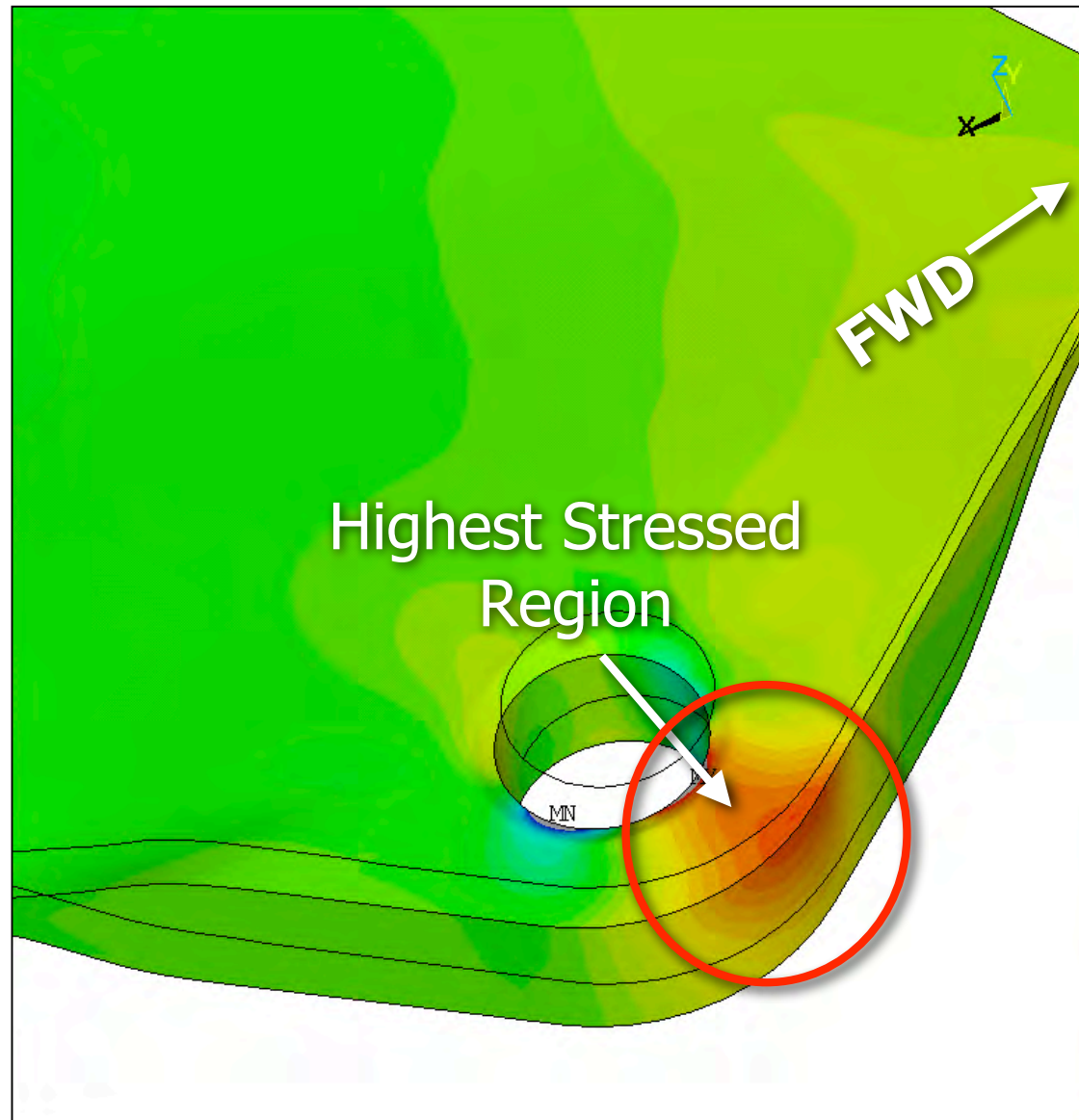
LUG STRENGTH DETERMINATION

The strength of the lug was determined by:

- Finite element analysis
- Progressive failure analysis
- Post accident lug tests

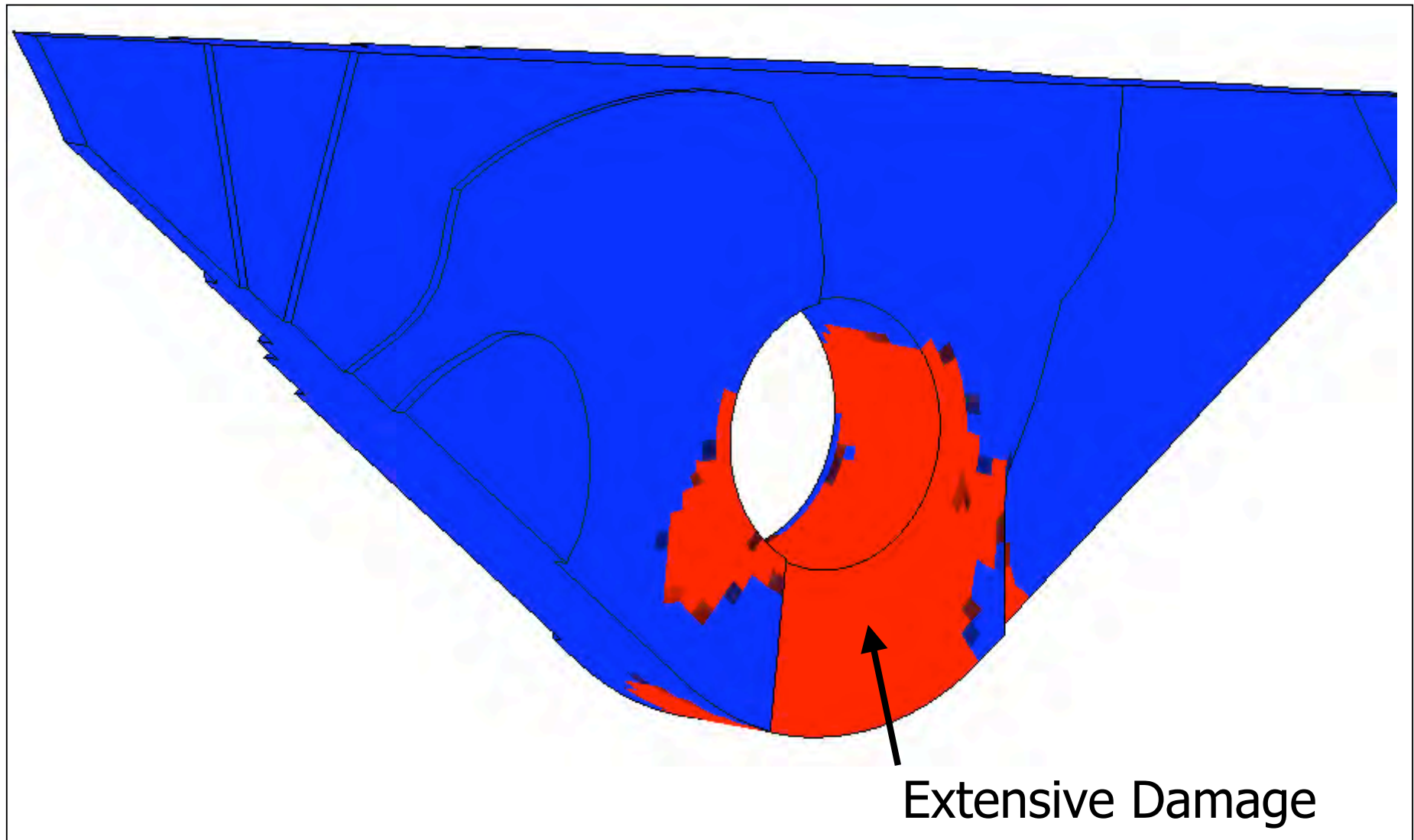


FINITE ELEMENT ANALYSIS OF THE LUG





PROGRESSIVE FAILURE ANALYSIS



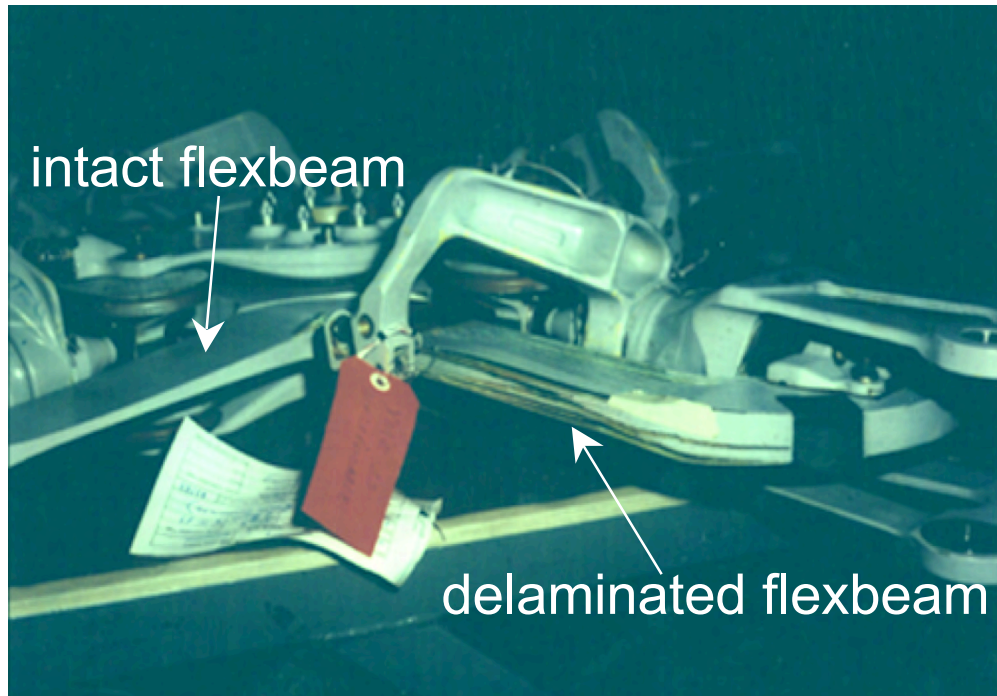


FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM

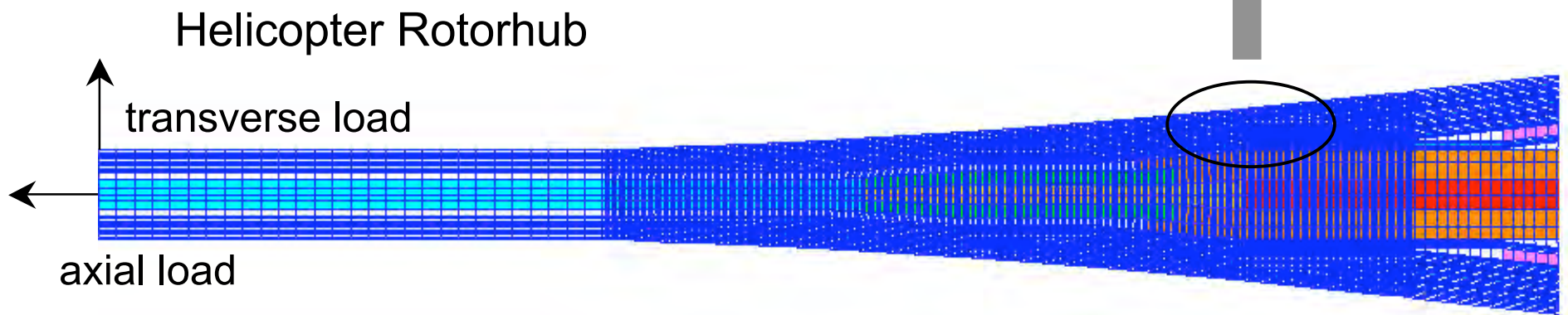
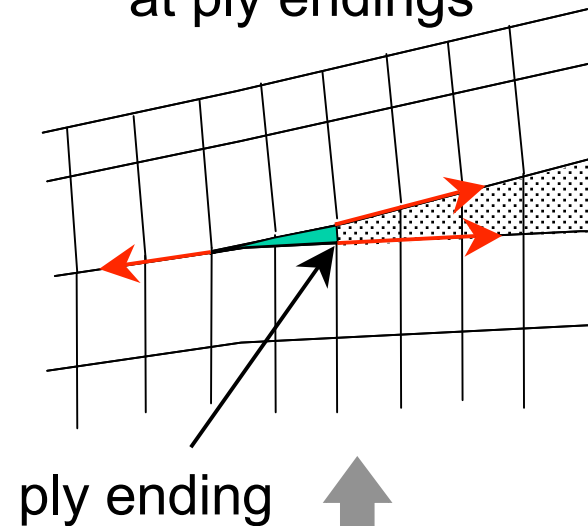
**GRETCHEN MURRI
U.S. ARMY RESEARCH LABORATORY, VEHICLE
TECHNOLOGY DIRECTORATE**

**Resident at Durability, Damage Tolerance and Reliability
Branch, NASA Langley Research Center**

FINITE ELEMENT MODEL OF DELAMINATION IN A ROTORHUB FLEXBEAM



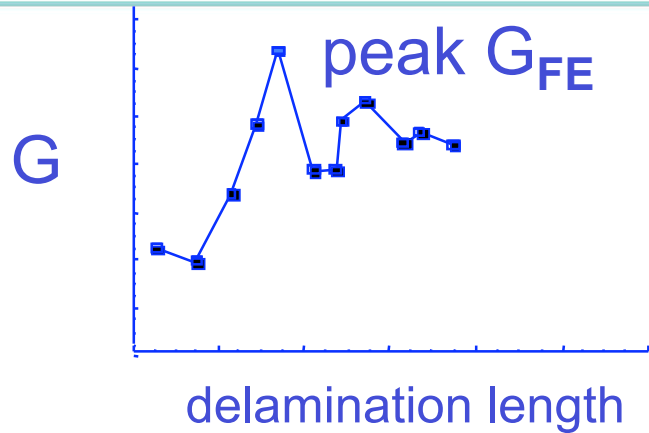
Delaminations initiate at ply endings



Finite element model of flexbeam with internal ply-drops

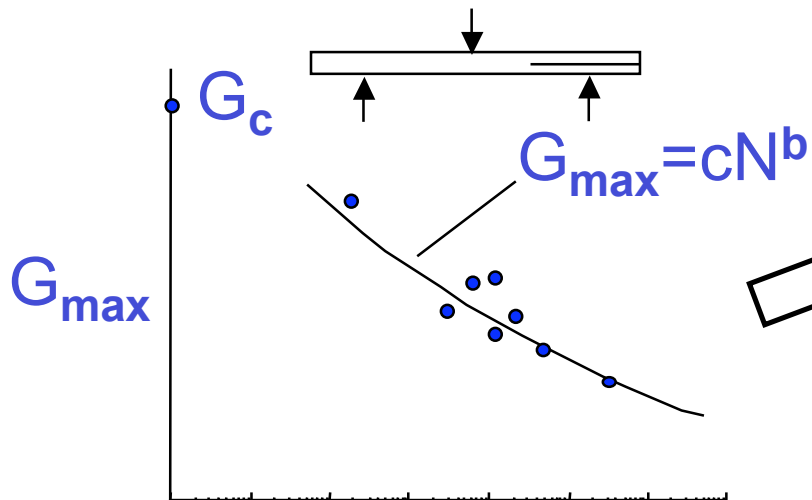


FLEXBEAM FATIGUE LIFE METHODOLOGY



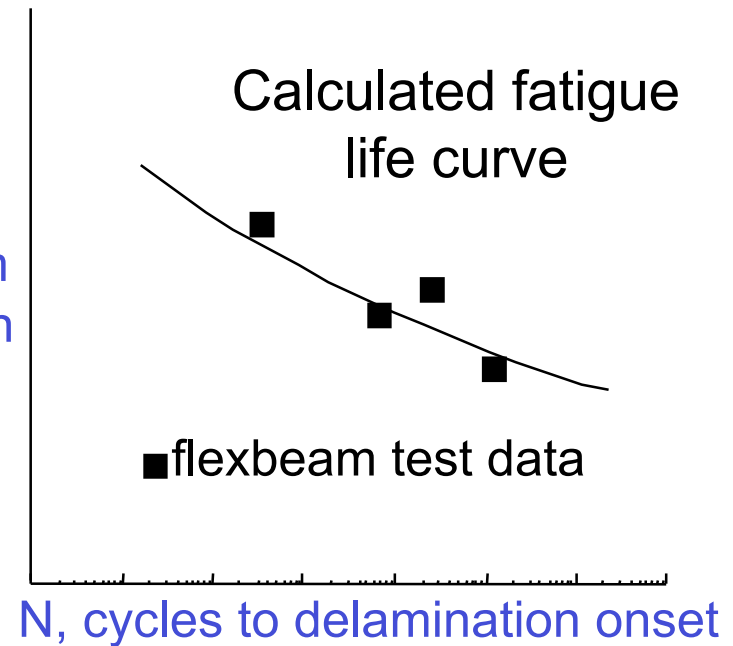
VCCT used to calculate G as delamination grows

flex-beam strain



N , cycles to delamination onset

Fatigue toughness data for modeled material





MIXED-MODE FAILURE CRITERIA FOR DELAMINATION IN COMPOSITE LAMINATES

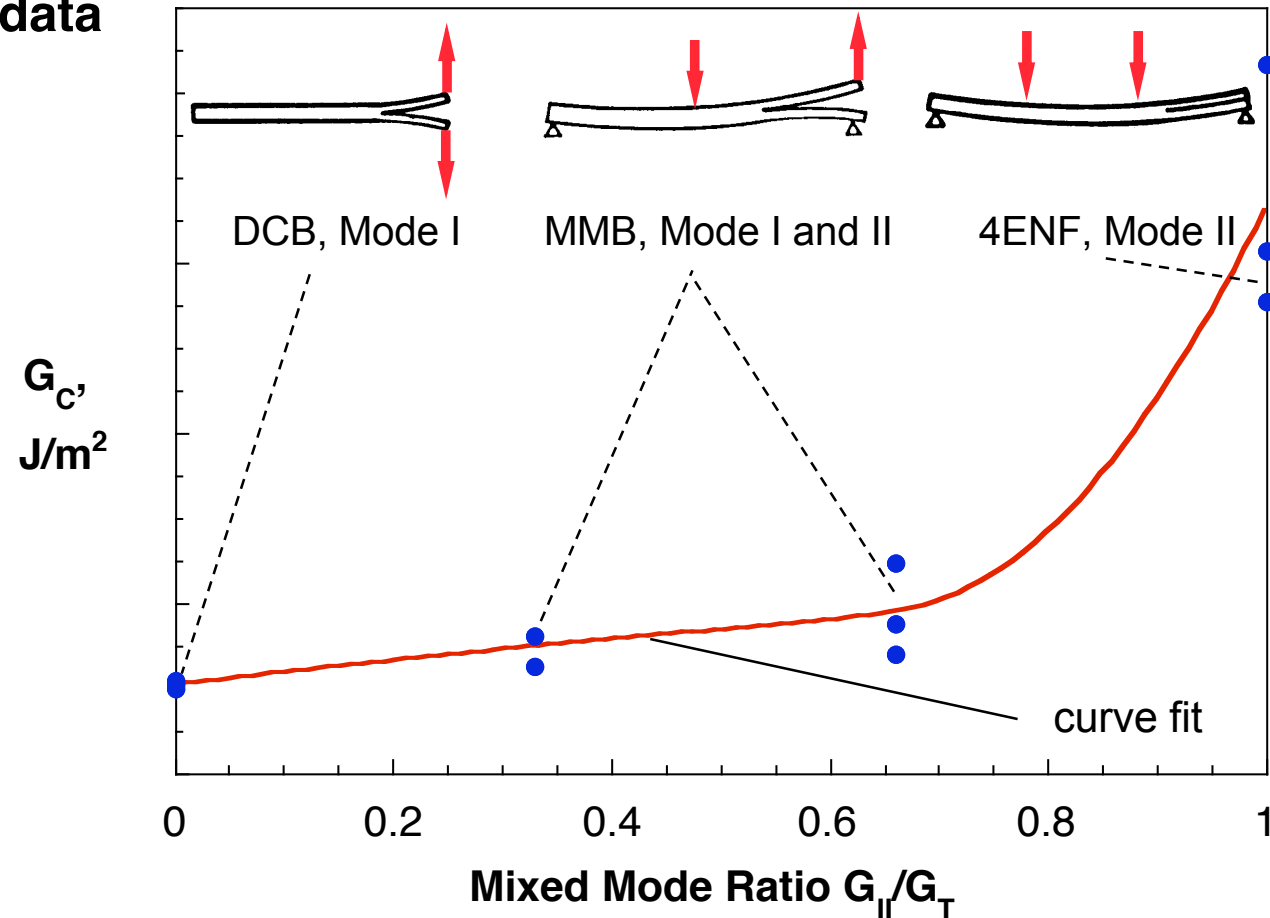
JAMES REEDER

**NASA LANGLEY RESEARCH CENTER
HAMPTON, VA**



2D MIXED MODE FRACTURE CRITERION

- Experimental data



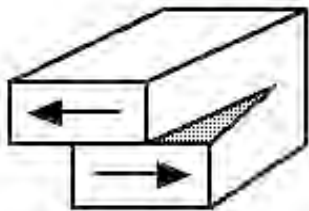
- Curve fit equation by Benzeggagh and Kenane, 1996

$$G_c = \left(G_{Ic} + (G_{IIc} - G_{Ic}) \cdot \left(\frac{G_{II}}{G_T} \right)^\eta \right)$$

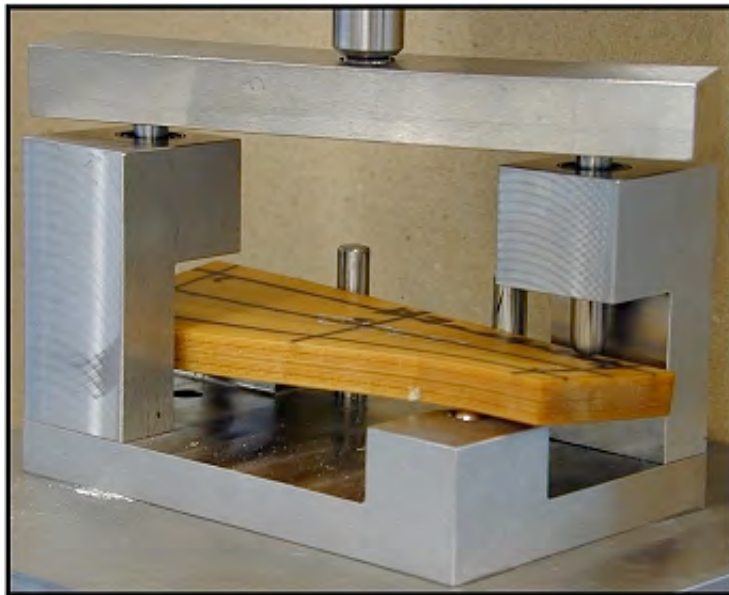


PROPOSED 3D MIXED MODE FRACTURE CRITERION

- Mode III - ECT Specimen



tearing
mode III

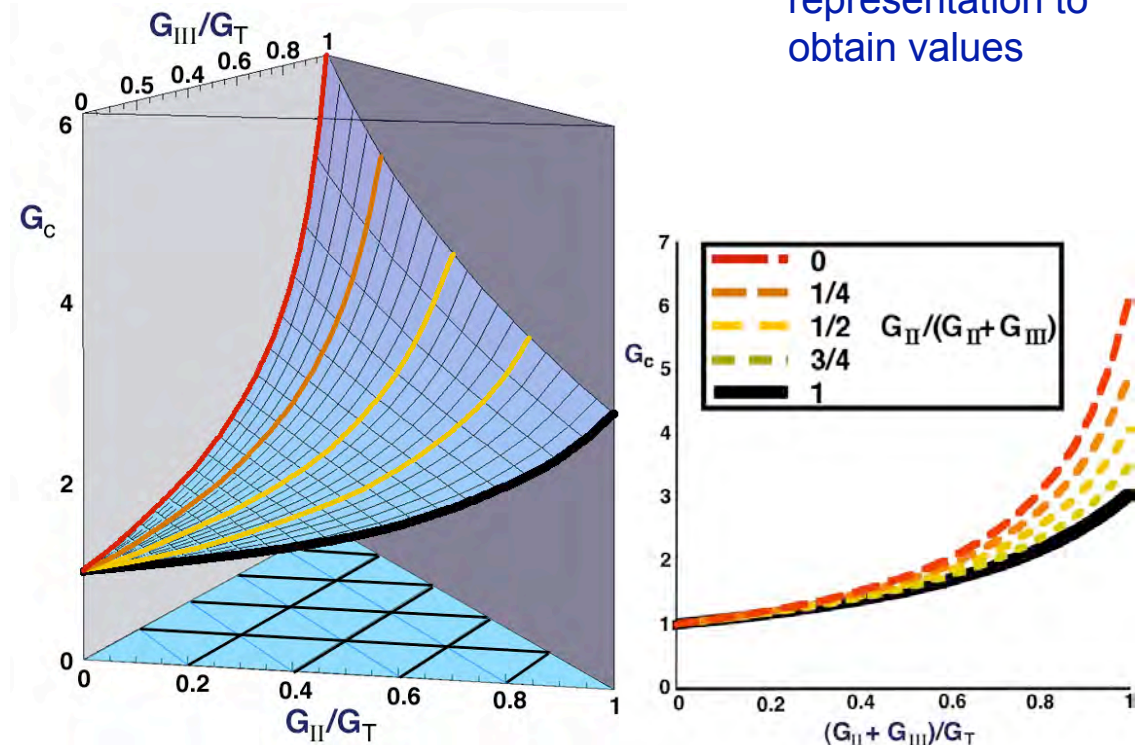


- Proposed 3D failure criterion**

$$\frac{G_T}{G_{Ic} + (G_{IIc} - G_{Ic}) \left(\frac{G_{II} + G_{III}}{G_T} \right)^\eta + (G_{IIIc} - G_{IIc}) \frac{G_{III}}{G_{II} + G_{III}} \left(\frac{G_{II} + G_{III}}{G_T} \right)^\eta} \geq 1$$

- Surface representation

- 2D plot representation to obtain values



**James Reeder, NASA Langley Research Center



ANALYSIS TO PREDICT DELAMINATION IN Z-PIN REINFORCED LAMINATES

**JAMES RATCLIFFE
NATIONAL INSTITUTE OF AEROSPACE
HAMPTON, VA**

**Resident at Durability, Damage Tolerance and
Reliability Branch, NASA Langley Research Center**



Z-PIN TECHNOLOGY

Definition

- Pultruded graphite rods positioned through-thickness (z-direction) of a composite laminate
- Pins are 0.2-0.5mm diameter rods
- Typical range of areal density between 0.5% and 4%
- Inserted into uncured laminate using ultrasonic hammer

Purposes

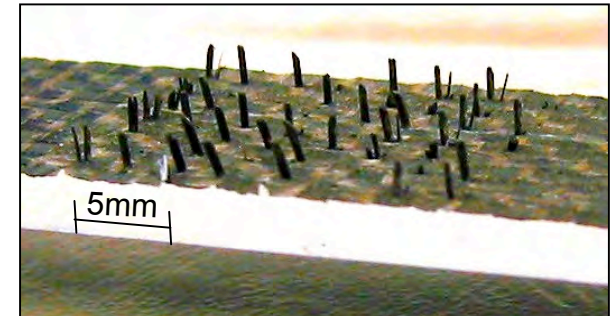
- Improve composite laminate transverse strength
- Prohibit delamination

Drawbacks

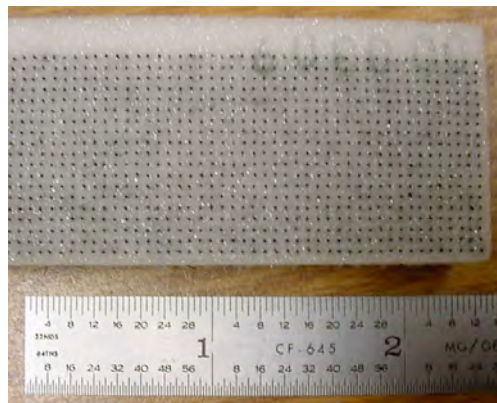
- Degrade laminate (in-plane) properties

Applications

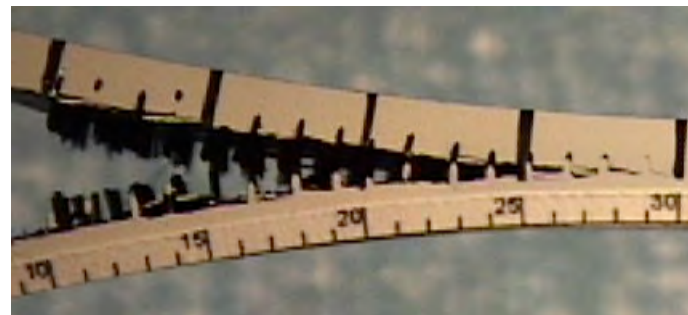
- F/A 18 inlet ducts, X-cor™, Formula 1 auto racing



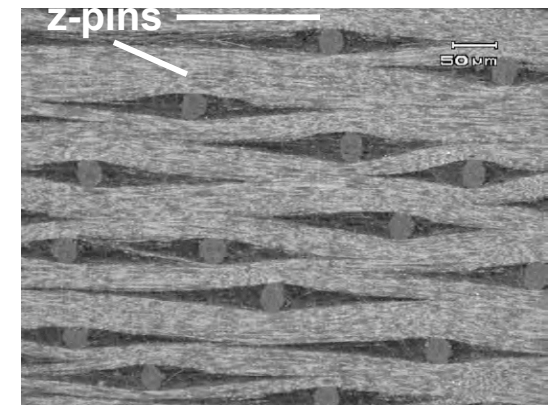
Z-Pins protruding from laminate



Z-Pin preform: Insertion side*



Z-pin bridging mode I delamination



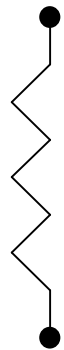
Fiber misalignment from z-pins**



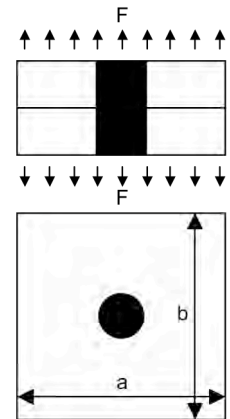
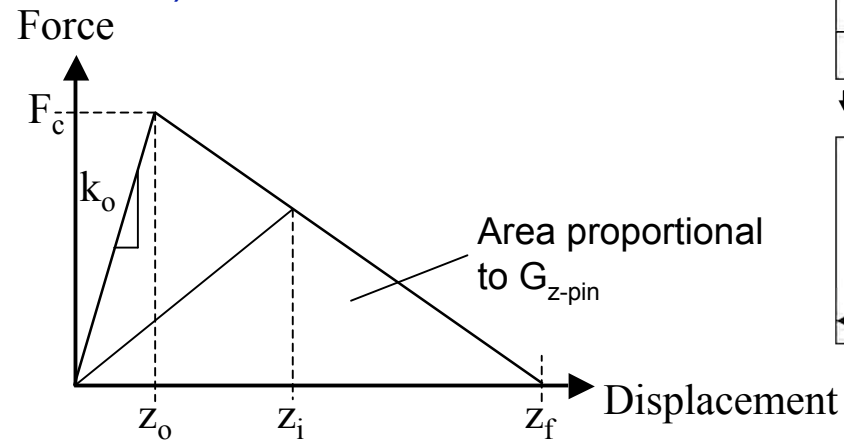
FINITE ELEMENT ANALYSIS

1 Discrete spring used to represent individual z-pins

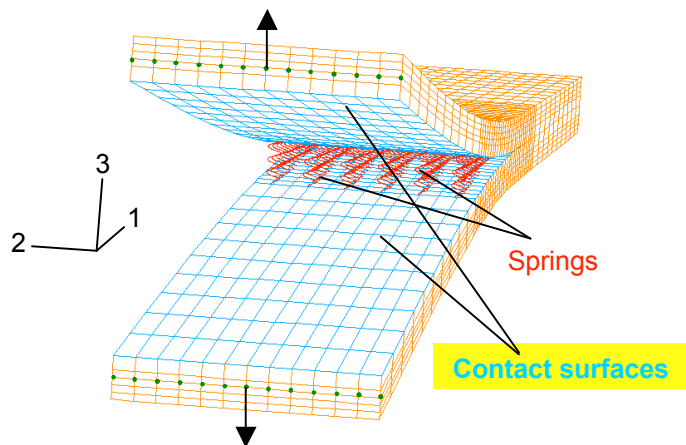
(Traction law assigned for representing z-pin failure)



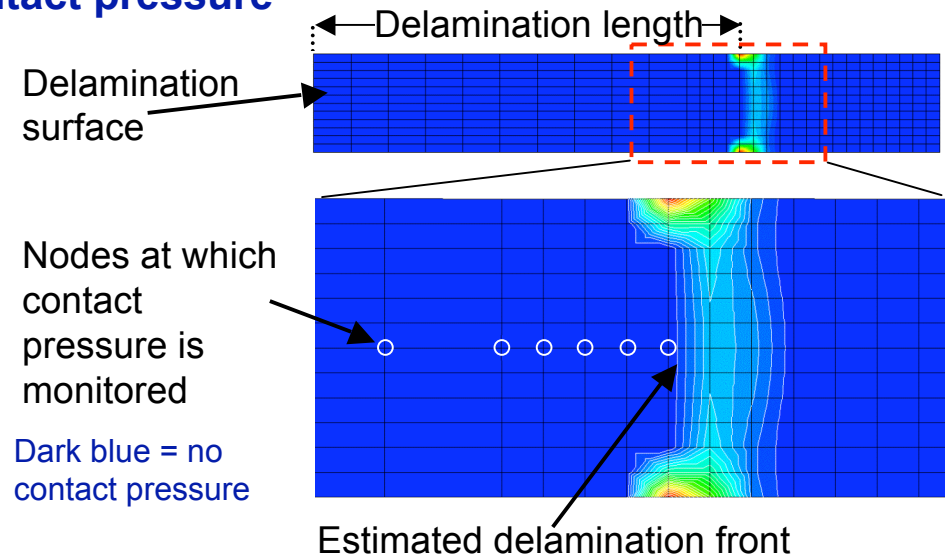
$$k_i = \begin{cases} k_o & \Leftarrow z_i \leq z_o \\ (1-d)k_o & \Leftarrow z_o \leq z_i \leq z_f \\ 0 & \Leftarrow z_i \geq z_f \end{cases}$$



2 Springs inserted into finite element model



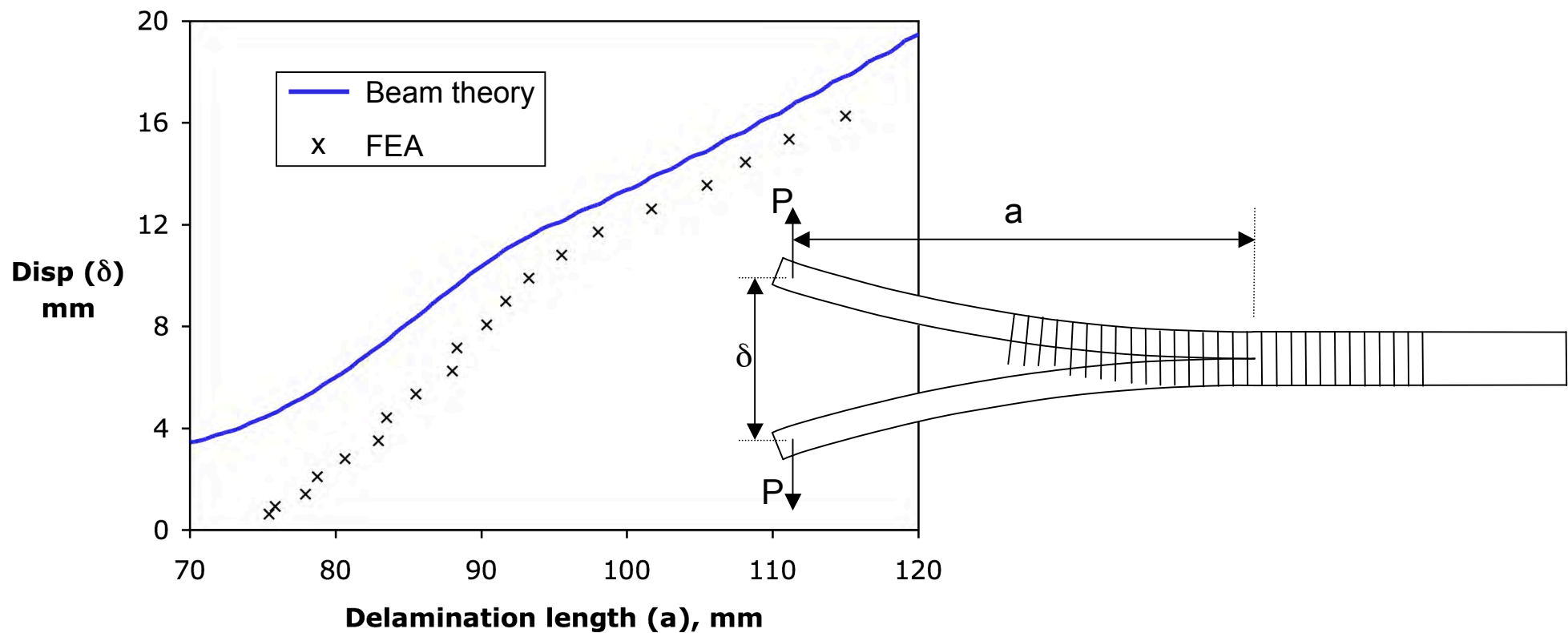
3 Delamination growth tracked using contact pressure





COMPARISON WITH BEAM THEORY

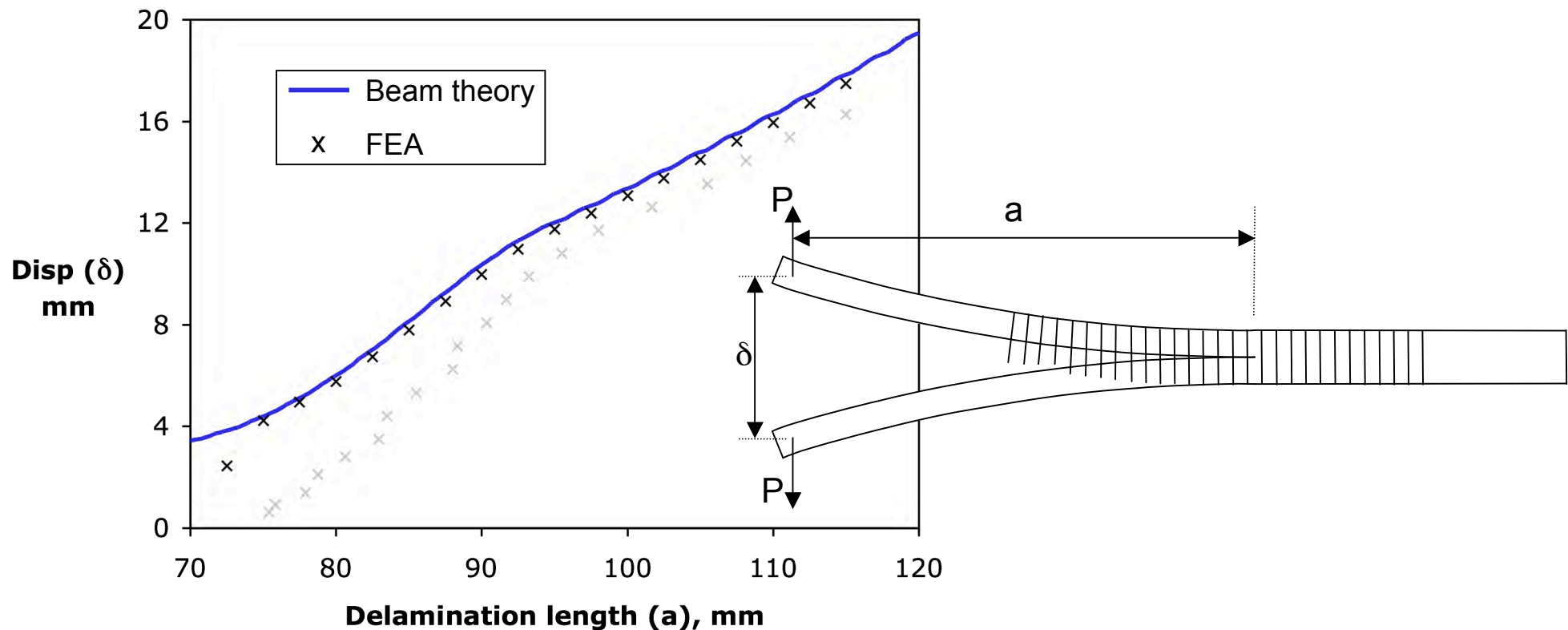
- Finite element analysis overestimates delamination length for a given displacement





COMPARISON WITH BEAM THEORY

- Finite element analysis results in better agreement with beam theory when decohesion elements used for delamination





CONCLUDING REMARKS

- Many analysis studies involve a low Technology Readiness Level (TRL). Therefore, specialized tools are required which are not always commercially available
- In many cases the finite element analysis software has to provide input to specialized user subroutines. An adequate interface is required to enable appropriate communication with the user subroutines.
- The specialized analysis tools are often computationally expensive